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Chern et al.

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(54) **TEMPERATURE SENSING CIRCUIT**

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(60) Provisional application No. 61/171,684, filed on Apr. 22, 2009.

(57) **ABSTRACT**

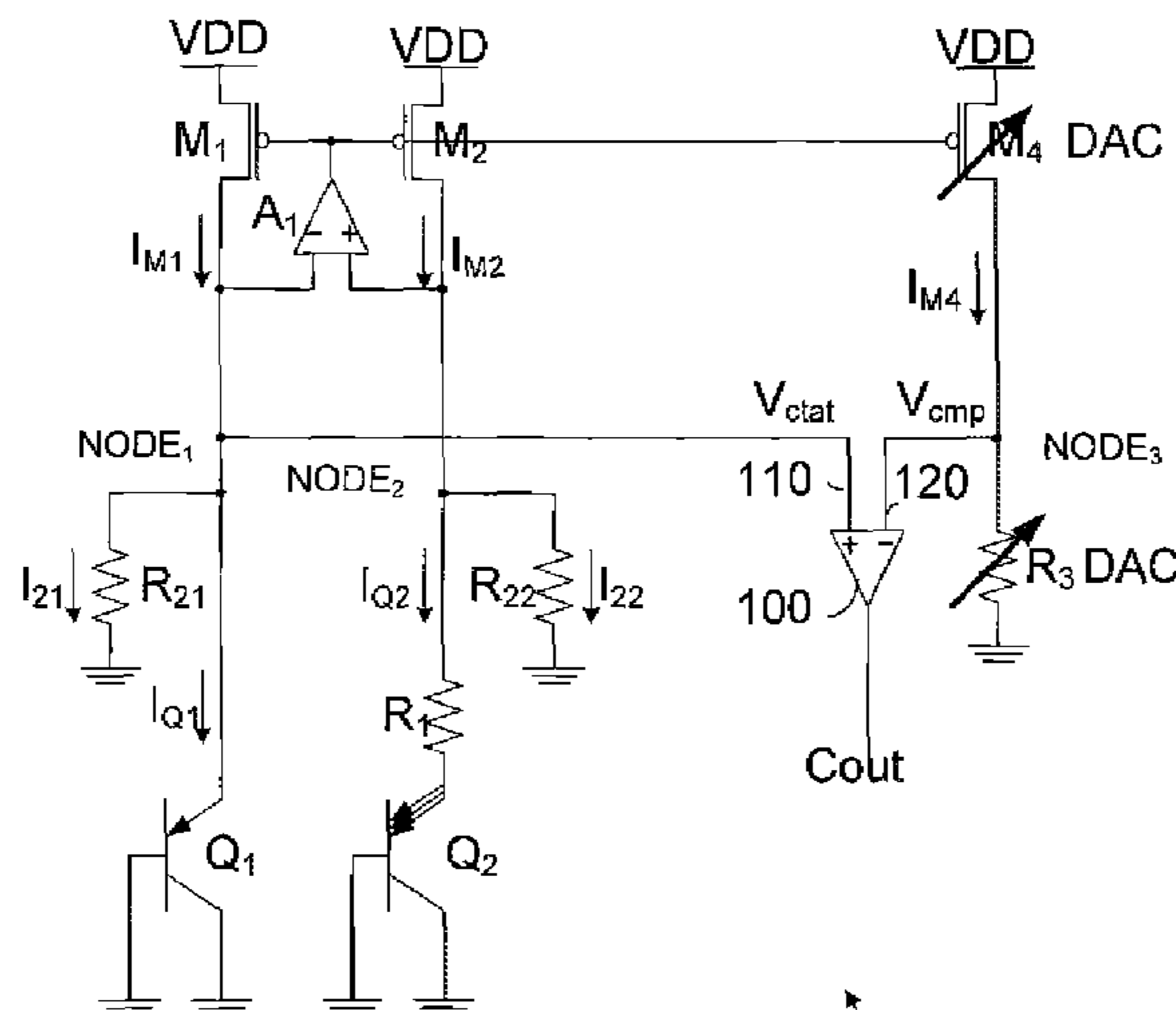
(51) **Int. Cl.**
G01K 7/14 (2006.01)
G01K 7/01 (2006.01)

A circuit includes a comparator, a first circuit, and a second circuit. The comparator has a first input node and a second input node. The first circuit is configured to output a temperature-dependent voltage at the first input node of the comparator. The first circuit includes a current mirror configured to generate a first reference voltage. The second circuit is configured to output a second reference voltage at the second input node of the comparator responsive to a digital code and the first reference voltage.

(52) **U.S. Cl.**
CPC .. **G01K 7/14** (2013.01); **G01K 7/01** (2013.01);
G01K 2219/00 (2013.01)

(58) **Field of Classification Search**
CPC G01K 7/02; G01K 7/00; G01K 7/14
USPC 374/170-172, 178, 180, 147
See application file for complete search history.

20 Claims, 12 Drawing Sheets



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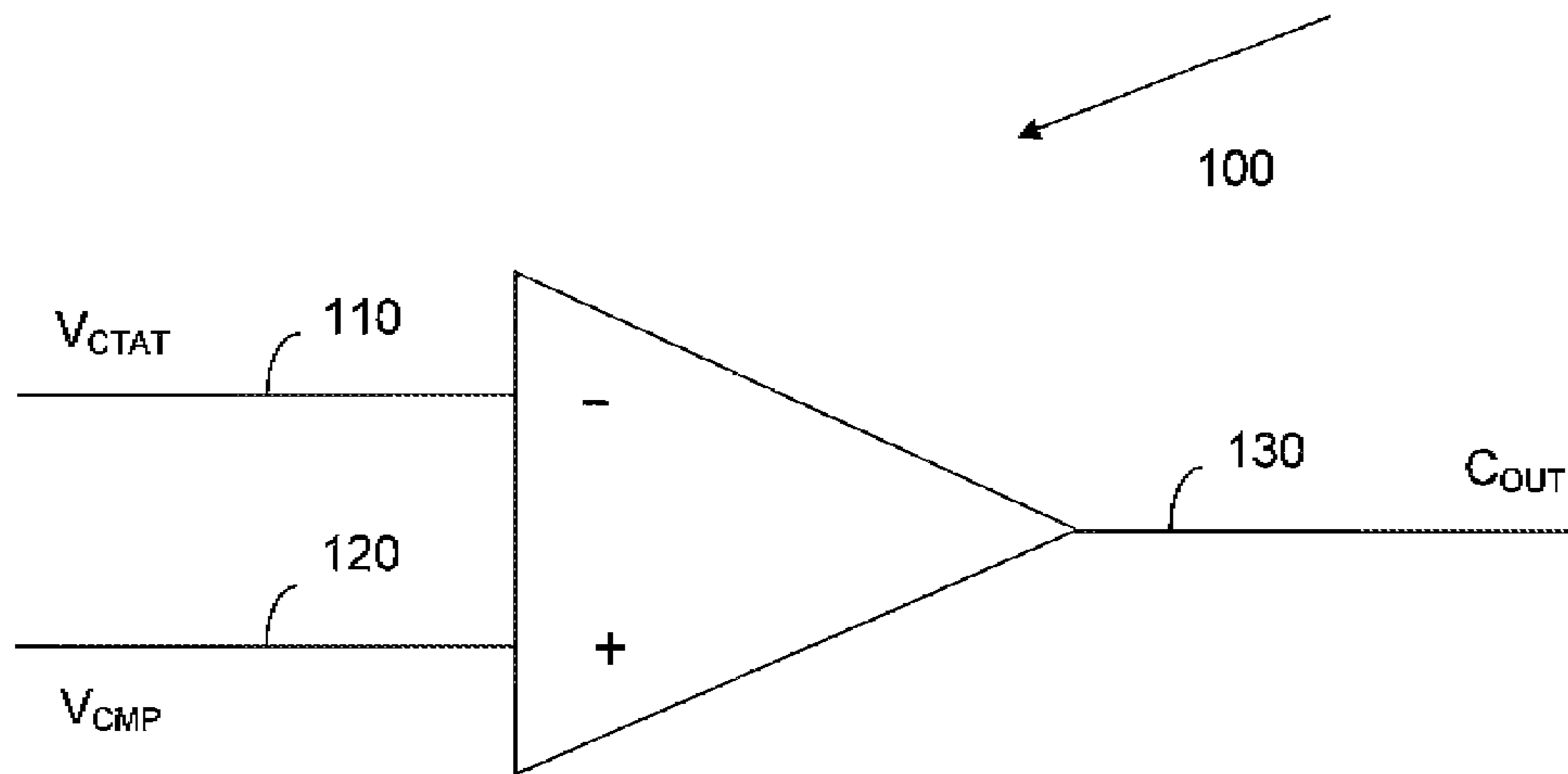


Fig. 1

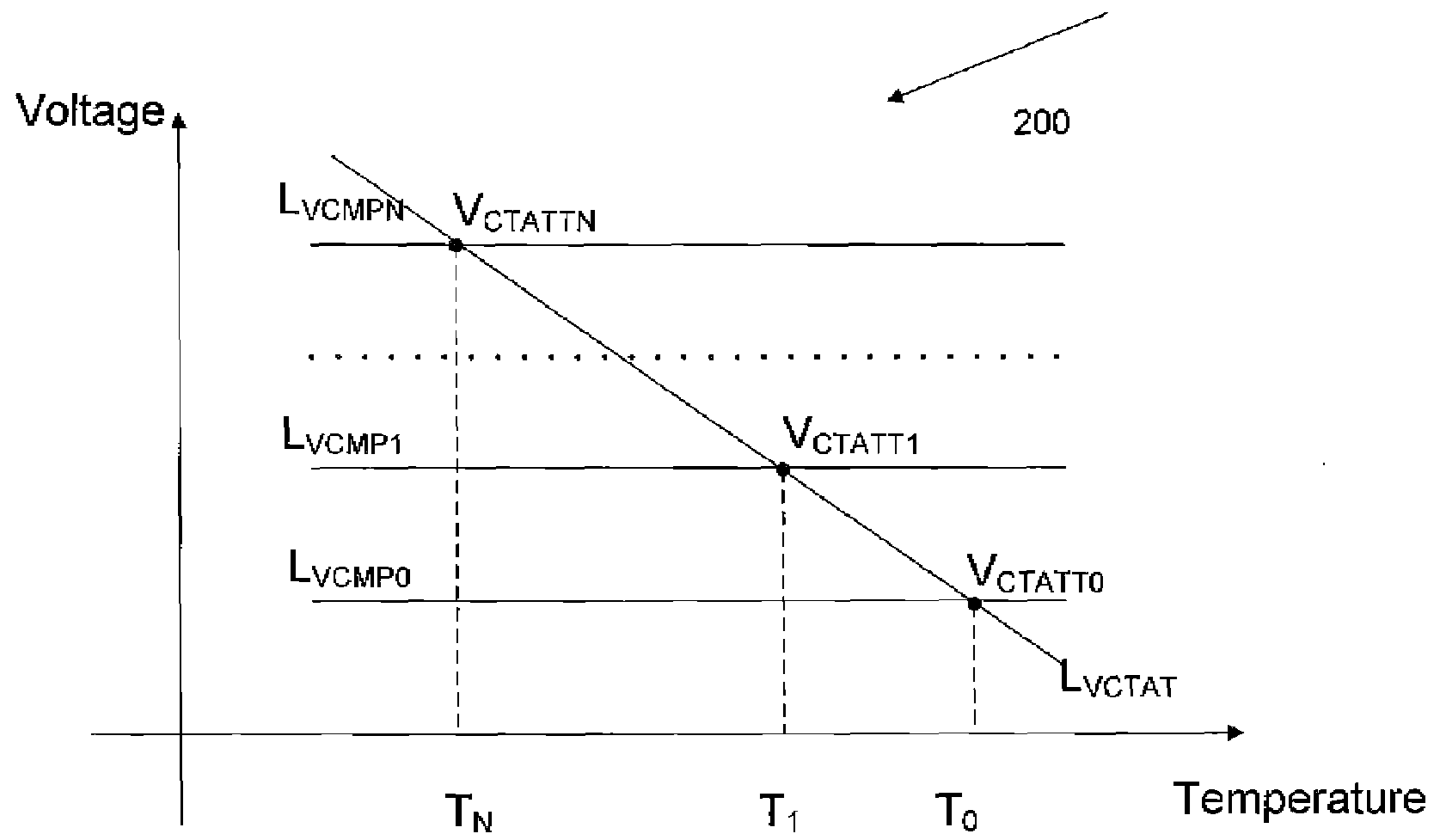


Fig. 2

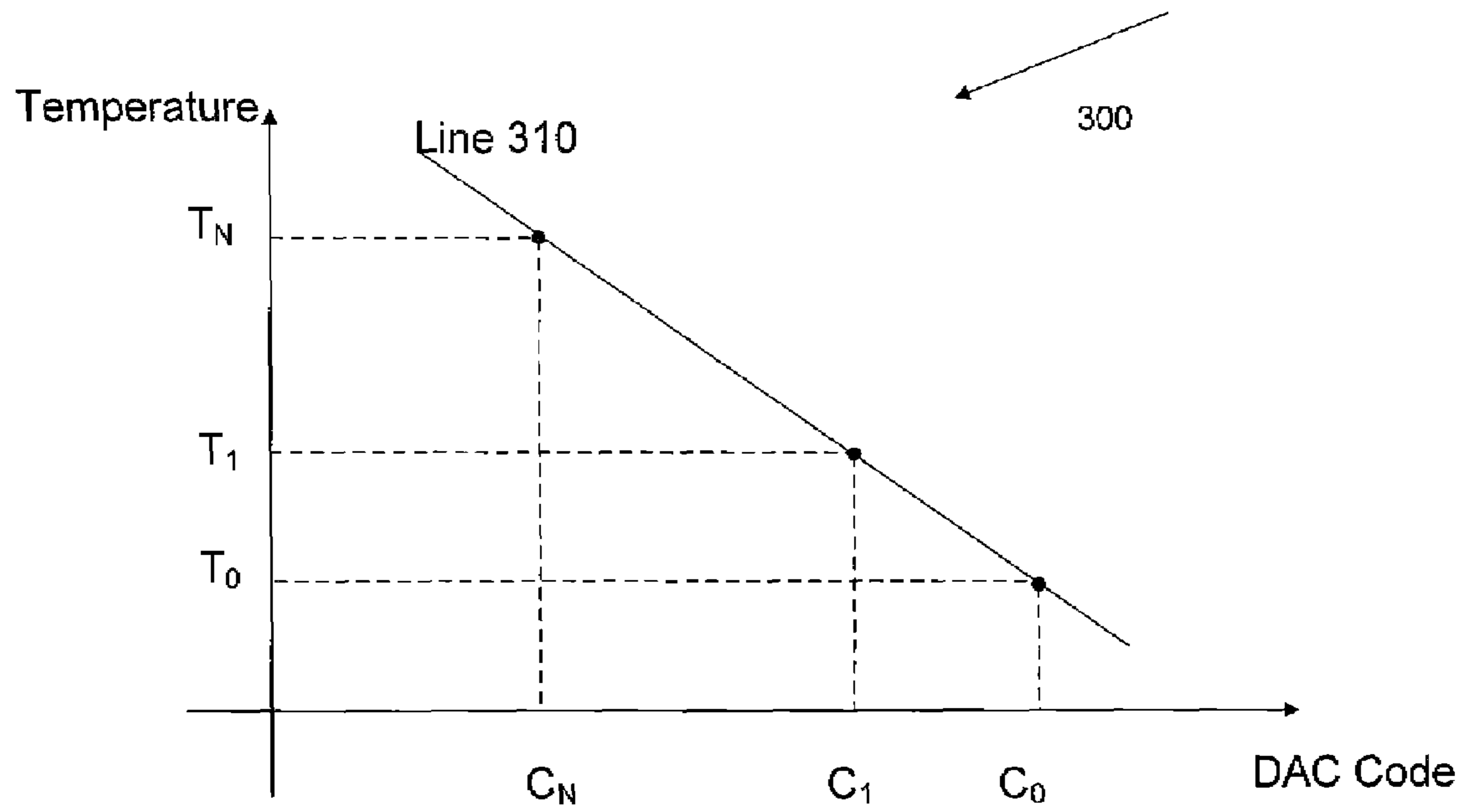


Fig. 3

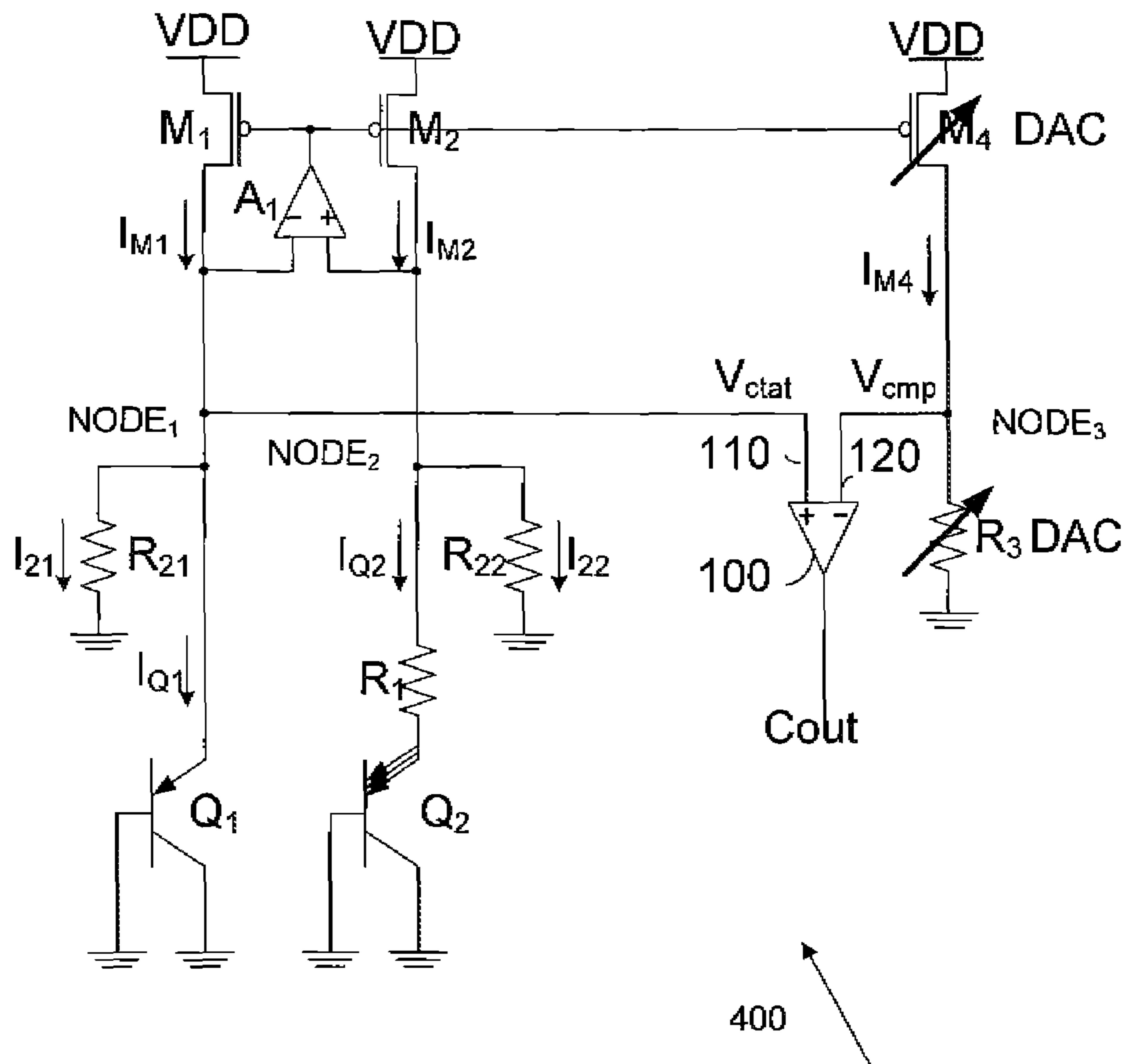


Fig. 4

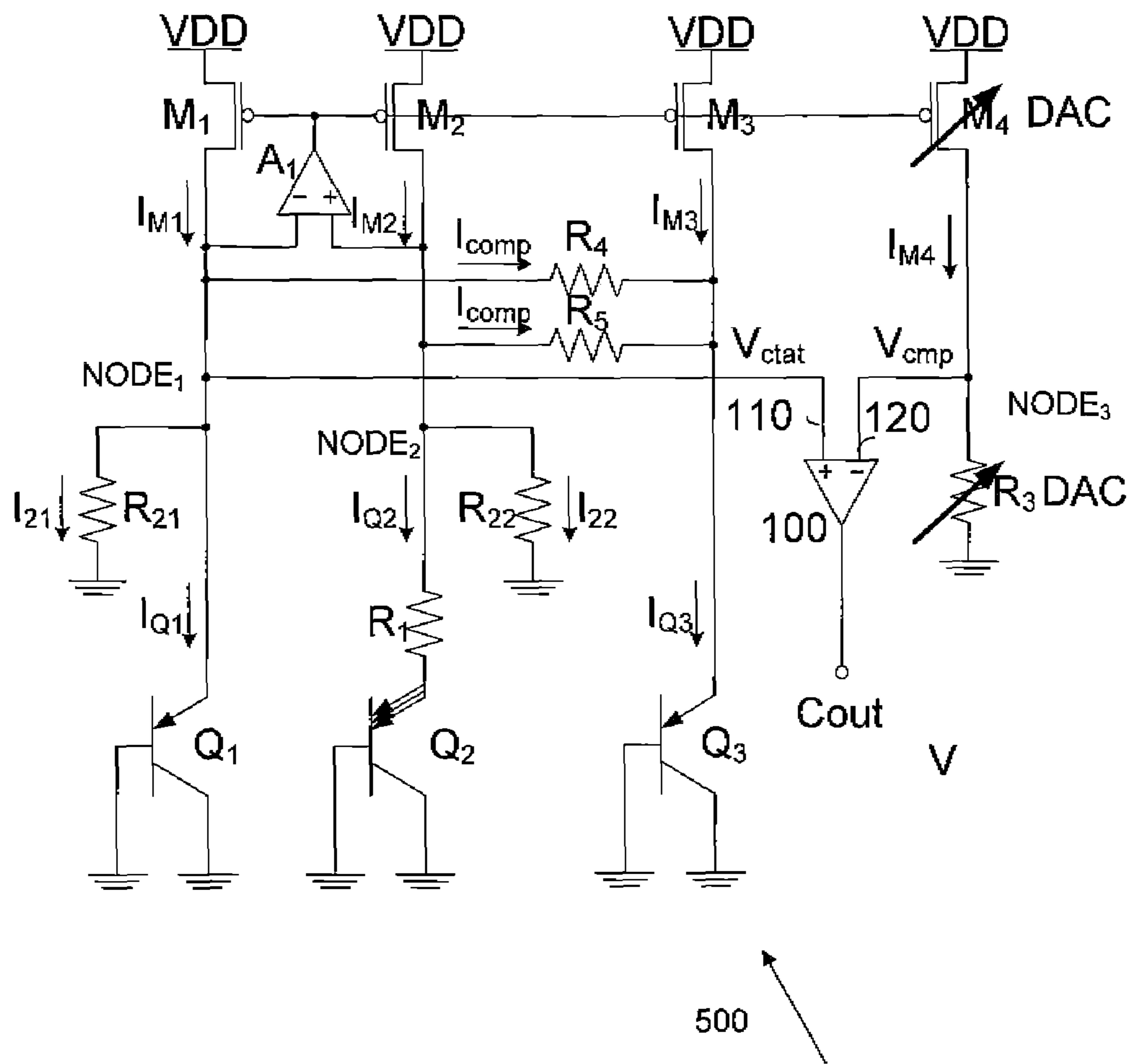


Fig. 5

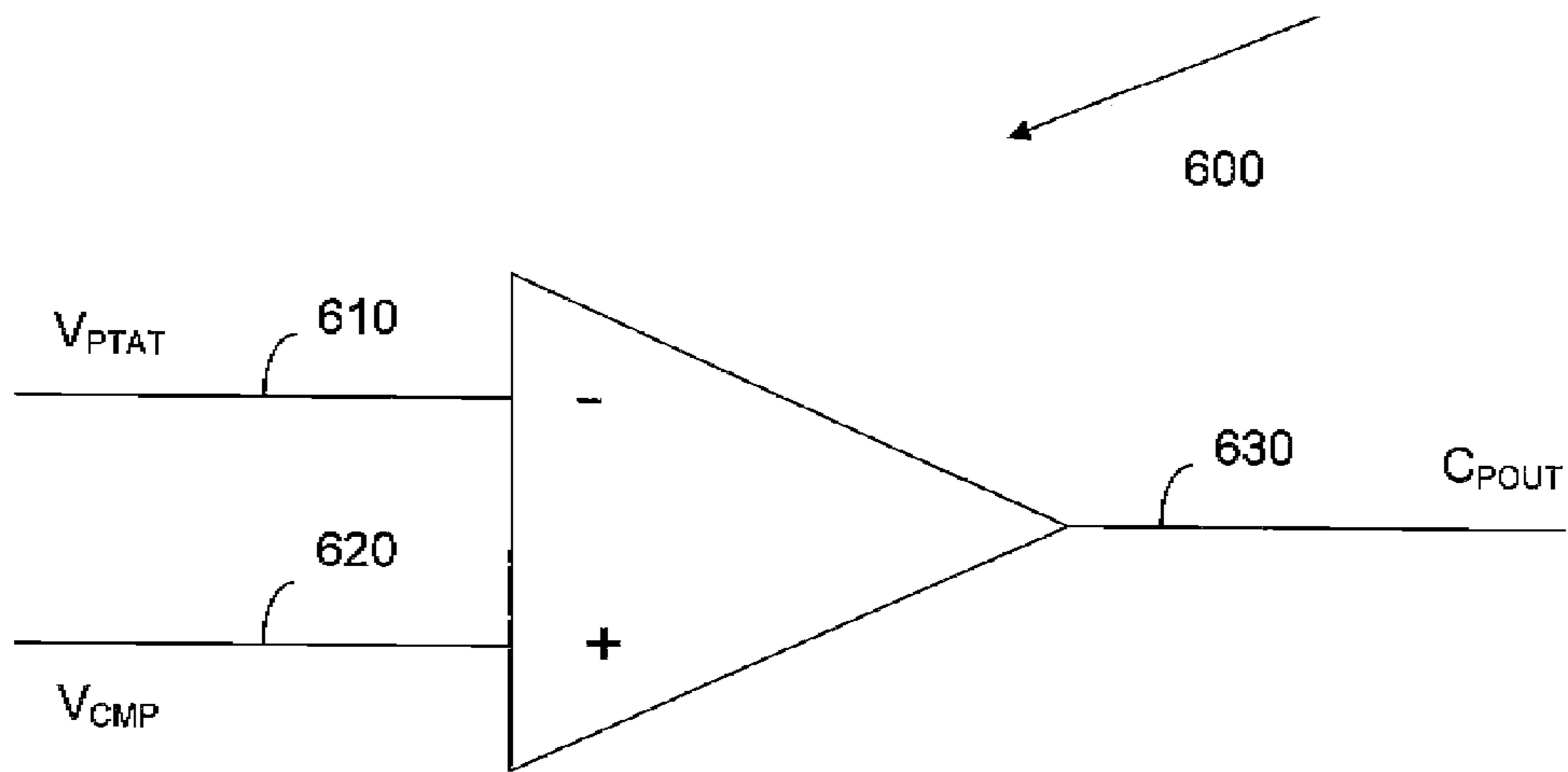


Fig. 6

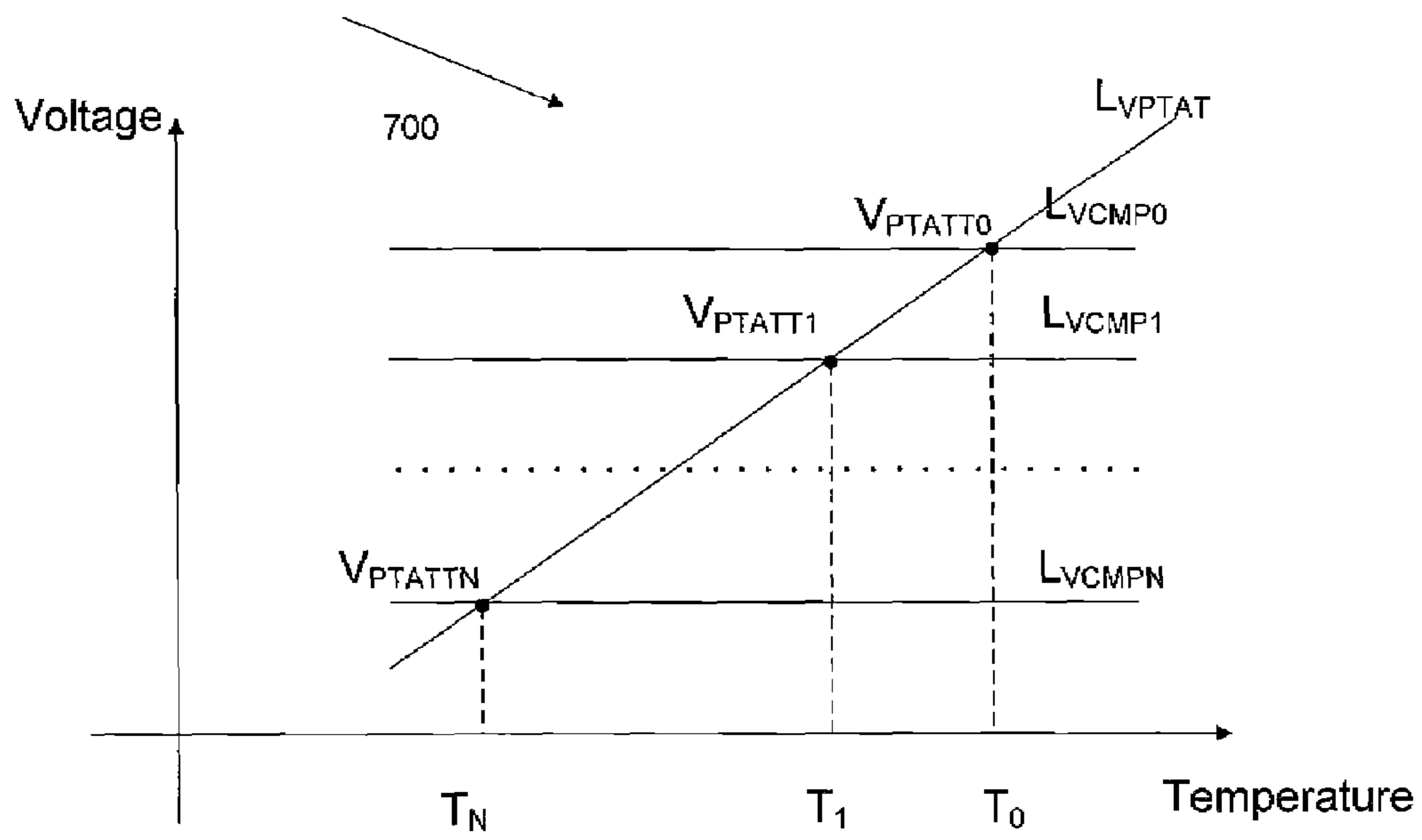


Fig. 7

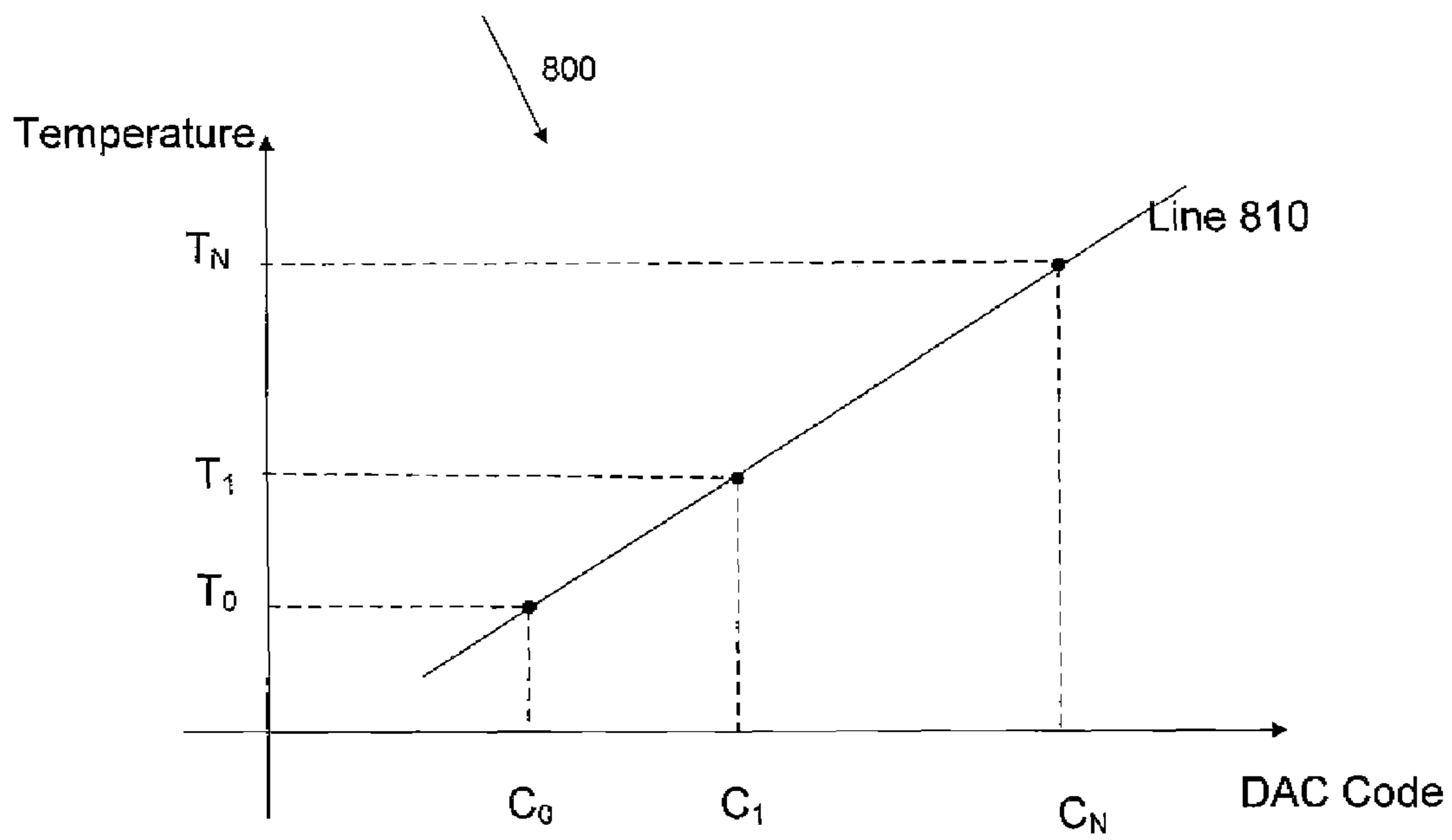


Fig. 8

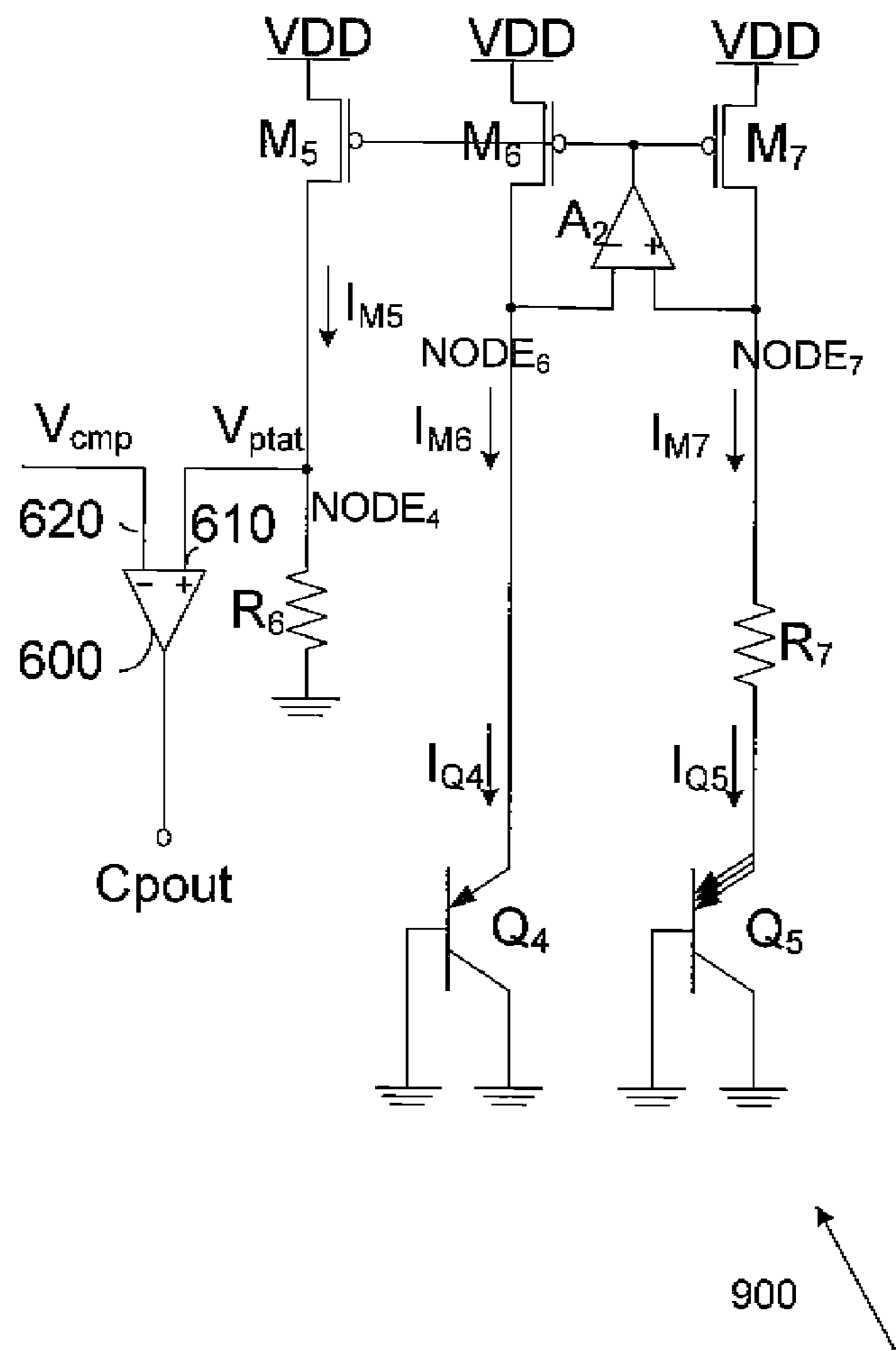


Fig. 9

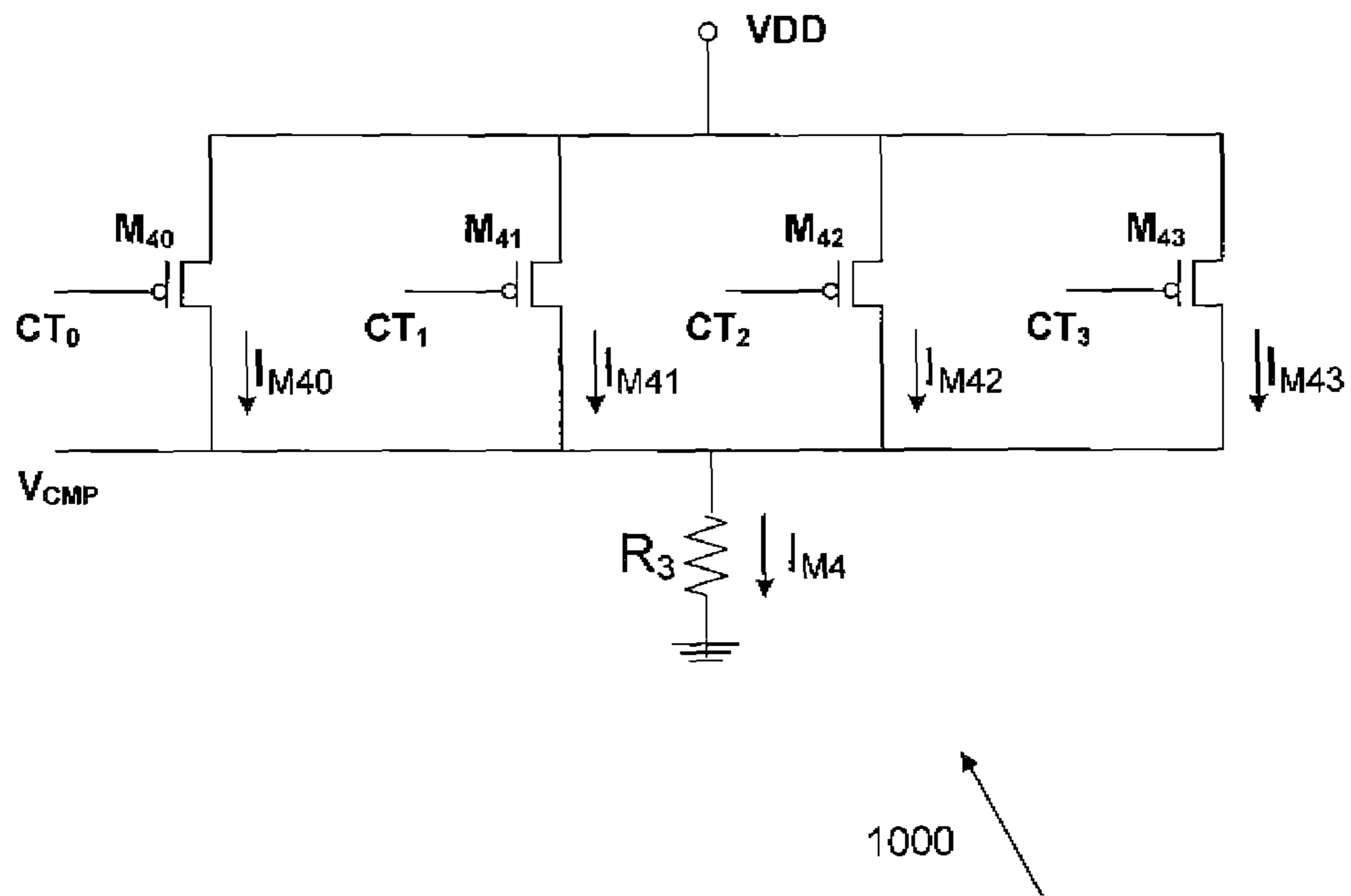


Fig. 10

L	M ₄₀	M ₄₁	M ₄₂	M ₄₃
0	ON	OFF	OFF	OFF
1	ON	ON	OFF	OFF
2	ON	ON	ON	OFF
3	ON	ON	ON	ON


1100 

Fig. 11

L	CT ₀	CT ₁	CT ₂	CT ₃
0	0	1	1	1
1	0	0	1	1
2	0	0	0	1
3	0	0	0	0


1200 

Fig. 12

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TEMPERATURE SENSING CIRCUIT

CROSS-REFERENCE TO RELATED
APPLICATIONS

The present application is a continuation of U.S. application Ser. No. 12/764,532, filed Apr. 21, 2010, which claims the priority of U.S. Provisional Application No. 61/171,684, filed on Apr. 22, 2009, which are incorporated herein by reference in their entireties.

TECHNICAL FIELD

Embodiments of the disclosure are related to generating linear relationship between temperatures and digital codes. Various embodiments are used in temperature sensors.

BACKGROUND

A temperature sensor can be used to monitor temperature of an electronic component such as a CPU (Central Processing Unit), GPU (Graphics Processing Unit), MPU (Micro Processing Unit), SOC (System On Chip), etc. When the temperature exceeds predetermined thresholds, the sensor may alert a circuitry to slow down or even shut down the unit to reduce power consumption and thus reduce the temperature so that overheating that can cause destructive failure to the unit may be prevented.

Typically, temperature sensors include a reference circuitry and a temperature measuring circuitry wherein the temperature dependency is either proportional to absolute temperature (PTAT), that is, the measuring circuit outputs a voltage that increases in proportion to a temperature rise or has a positive temperature coefficient, or complementary to absolute temperature (CTAT), that is, the measuring circuit outputs a voltage that drops in proportion to a temperature rise or has a negative temperature coefficient. Further, DAC (digital to analog converter) based temperature sensors relying on comparing a PTAT voltage and a CTAT base-emitter voltage may be used. This approach, however, suffers from DAC code-to-temperature non-linearity issues, i.e., it cannot achieve good linearity over a wide temperature range, resulting in poor temperature measurement accuracy.

In some approaches involving a CTAT voltage, the compared voltage varies with high temperature coefficient over the design temperature range. When the compared voltage is PTAT, the implementation scheme introduces an intrinsic DAC code-to-temperature nonlinearity, and, as a result, suffers from poor temperature measurement accuracy unless an extensive temperature calibration (e.g., many-point calibration) is performed. Other approaches trying to cause the compared (or reference) voltage family curves to be parallel, and thus better DAC code-to-temperature linearity, are far from successful because the curves, in reality, are not parallel. These approaches therefore also suffer from poor temperature measurement accuracy.

BRIEF DESCRIPTION OF THE DRAWINGS

The details of one or more embodiments are set forth in the accompanying drawings and the description below. Other features and advantages of the disclosure will be apparent from the description, drawings, and claims.

FIG. 1 shows a circuit 100 related to a CTAT-type implementation in accordance with an embodiment.

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FIG. 2 shows a graph 200 illustrating the relationship between temperature and various voltages in accordance with the CTAT-type embodiments.

FIG. 3 shows a graph 300 illustrating the relationship between the DAC code and temperature in accordance with the CTAT-type embodiments.

FIG. 4 shows a circuit 400 used to create V_{CTAT} and V_{CMP} in accordance with a first embodiment.

FIG. 5 shows a circuit 500 used to create V_{CTAT} and V_{CMP} in accordance with a second embodiment.

FIG. 6 shows a circuit 600 related to a PTAT-type implementation in accordance with an embodiment.

FIG. 7 shows a graph 700 illustrating the relationship between temperature and various voltages in accordance with the PTAT-type embodiments.

FIG. 8 shows a graph 800 illustrating the relationship between the DAC code and temperature in accordance with the PTAT-type embodiments.

FIG. 9 shows a circuit 900 used to generate V_{PTAT} in accordance with an embodiment.

FIG. 10 shows an exemplary circuit 1000 illustrating an implementation of DAC transistors M_4 .

FIG. 11 shows a table 1100 illustrating correspondence between values that can be used as digital codes and the number of transistors M_4 in circuit 1000 being turned on or off.

FIG. 12 shows a table 1200 illustrating the relationship between values that can be used as digital codes and signals CT in FIG. 10.

Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

Some embodiments of the disclosure relate to providing linear relationship between temperatures and digital codes. Various embodiments are used in temperature sensors. In some embodiments, at a particular temperature (e.g., operational temperature of a semiconductor device), a circuit (e.g., temperature sensing circuit) in the sensor provides a temperature dependent reference voltage, e.g., V_{CTAT} and a compared voltage, e.g., V_{CMP} , to a comparator. V_{CTAT} depends on temperature as complement to absolute temperature. The compared voltage V_{CMP} is generated having DAC codes as inputs. If V_{CTAT} and V_{CMP} are equal (e.g., substantially equal), then the comparator output so indicates, e.g., by providing a true logic. If V_{CTAT} and V_{CMP} are not equal, then the comparator output is provided to another circuit (e.g., an adjusting circuit) that varies the DAC codes until V_{CTAT} and V_{CMP} are equal. In effect, at a particular point in time, the temperature experienced by the temperature sensing circuit corresponds to a DAC code when V_{CTAT} and V_{CMP} are equal. In various embodiments, the various temperatures experienced by the temperature sensing circuit and the DAC codes are substantially linearly related. Other embodiments and embodiments related to a voltage that depends on temperature as proportional to absolute temperature (e.g., V_{PTAT}) are also disclosed.

Embodiments of the disclosure can have one or a combination of the following features and/or advantages. Embodiments of the temperature sensing circuit can be integrated in semiconductor circuitry manufactured by advanced CMOS (Complementary Metal Oxide Semiconductor) processes. The linear relationship between the temperatures and the DAC codes increases accuracy of the temperature sensing circuitry and allows simple temperature calibration that, in turn, enables accurate temperature sensing.

Embodiments, or examples, illustrated in the drawings are now described using specific language. It will nevertheless be understood that no limitation of the scope of the invention is thereby intended. Any alterations and modifications in the described embodiments, and any further applications of principles described in this document are contemplated as would normally occur to one skilled in the art to which the disclosure relates. Reference numbers may be repeated throughout the embodiments, but this does not necessarily require that features of one embodiment apply to another embodiment, even if they share the same reference number.

Voltage Dependent on Temperature as Complementary to Absolute Temperature (V_{CTAT})

FIG. 1 shows a comparator **100** in accordance with an embodiment related to a CTAT-type implementation. Reference voltage V_{CTAT} on line **110** and compared voltage V_{CMP} on line **120** are generated by a circuit (e.g., temperature sensing circuit) that will be described below. Comparator **100** compares voltages V_{CMP} and V_{CTAT} , and provides resulting signal C_{OUT} on line **130**. In various embodiments, V_{CMP} is a voltage that varies with a very small or insignificant temperature coefficient over a wide temperature range. Further, various V_{CMP} values are generated with DAC (digital-to-analog converter) codes as inputs. V_{CTAT} is a complementary to absolute temperature (CTAT) reference voltage and is generated by the temperature sensing circuit at a corresponding temperature. For example, in an application, the temperature sensing circuit is embedded as part of a sensor in a semiconductor device, e.g., a CPU. At operation, the CPU experiences a particular temperature (e.g., operational temperature) that is also experienced by the temperature sensing circuit, and V_{CTAT} is generated having this temperature as an input. In some embodiments, V_{CMP} is initially lower than V_{CTAT} , and C_{OUT} is false (e.g., having a low logic). V_{CMP} is then increased until V_{CMP} is slightly higher than (e.g., substantially equal to) V_{CTAT} then C_{OUT} is true (e.g., having a high logic). When V_{CMP} is lower than V_{CTAT} , signal C_{OUT} is provided to another circuit (e.g., an adjusting circuit (not shown)) that changes the DAC codes which in turn change V_{CMP} until V_{CMP} is slightly higher than (e.g., substantially equal to) V_{CTAT} . In effect, when V_{CMP} is equal to V_{CTAT} , the temperature experienced by the CPU and the temperature sensing circuit, e.g., temperature T_0 , is also the temperature at which the temperature sensing circuit provides V_{CTAT} . Further, this temperature T_0 corresponds to a DAC code, e.g., DAC code C_0 . In various embodiments, the temperatures at which the temperature sensing circuit provides V_{CTAT} and the DAC codes are substantially linearly related. Those skilled in the art will recognize that when the temperatures and the DAC codes are linearly related, the graph representing their relationship on a two dimensional axis is a straight line.

V_{CTAT} , V_{CMP} and Corresponding Temperatures

FIG. 2 shows a chart **200** illustrating the relationship between V_{CTAT} , V_{CMP} , and temperatures T , in accordance with an embodiment. Each line L_{VCMP} (including L_{VCMP0} , L_{VCMP1} , L_{VCMPN} , etc.) shows the relationship between a voltage V_{CMP} and temperature T at a particular DAC code serving as an input for V_{CMP} to be generated. Each line L_{VCMP} can be generated by obtaining various values of V_{CMP} at various temperatures (e.g., operational temperatures of a CPU at different time points). In various embodiments, a line L_{VCMP} is substantially independent of temperature. Varying the DAC codes from the least significant bit (LSB) to the most signifi-

cant bit (MSB) provides lines L_{VCMP} . For example, if the DAC receives a 2-bit input, e.g., Input (0:1), varying bits **0** to **1** provides 4 DAC codes that correspond to 4 lines L_{VCMP} . If the DAC receives a 3-bit input, e.g., Input (0:2), varying bits **0** to **2** provides 8 DAC codes that correspond to 8 lines L_{VCMP} , etc. Further, line L_{VCMP0} corresponds to a code C_0 , and shows the relationship between voltage V_{CMP} and temperature T at code C_0 . Line L_{VCMP1} corresponds to code C_1 , and shows the relationship between voltage V_{CMP} and temperature T at code C_1 . Line L_{VCMPN} corresponds to code N , and shows the relationship between voltage V_{CMP} and temperature T at code C_N , etc. In accordance with some embodiments, due to the nature of very small or insignificant temperature coefficient for V_{CMP} , lines L_{VCMP} are very close to parallel (e.g., substantially parallel) to one another in addition to being substantially straight although not necessarily parallel to the x-axis. Based on the parallelism of lines L_{VCMP} and their being straight lines, embodiments provide linearity between the temperatures T and the DAC codes.

Line L_{VCTAT} shows the relationship between V_{CTAT} and temperature T . Those skilled in the art will recognize that line L_{VCTAT} has a negative slope and indicates that V_{CTAT} has a negative temperature coefficient. The intersection between line L_{VCTAT} and a line L_{VCMP} indicates that V_{CTAT} equals to V_{CMP} at a particular temperature T that corresponds to a particular DAC code C . For example, point V_{CTAT0} indicates V_{CTAT} equals to V_{CMP} at a temperature T_0 that corresponds to a DAC code C_0 . Similarly, point V_{CTAT1} indicates V_{CTAT} equals to V_{CMP} at a temperature T_1 that corresponds to DAC code C_1 , and V_{CTATN} indicates V_{CTAT} equals to V_{CMP} at a temperature T_N that corresponds to a DAC code C_N , etc. In various embodiments, each point V_{CTATT} corresponds to the result in comparator **100** where V_{CMP} and V_{CTAT} are equal, e.g., when signal C_{OUT} is true, at a particular temperature T experienced by the temperature sensing circuit.

Temperatures and DAC Codes—CTAT-type

FIG. 3 shows a graph **300** with a line **310** indicating the relationship between temperatures T and DAC codes C related to V_{CTAT} . For example, T_0 corresponds to code C_0 , T_1 corresponds to code C_1 , T_N corresponds to code C_N , etc.

Embodiments provide the linearity between temperatures T and DAC codes C as much as possible, which is advantageous over prior art approaches that do not provide such linearity. This linearity results from the fact that lines L_{VCMP} in FIG. 2 are substantially straight and substantially parallel to one another but do not need to be parallel to the x-axis. In a 100% linearity situation, lines L_{VCMP} are 100% straight and thus 100% parallel to one another, which results in a line **310** being 100% straight. In other approaches lines L_{VCMP} are curved and/or not parallel to one another, which also causes line **310** to be curved. Those skilled in the art will recognize that the less curved the line **310** is, the more linear the relationship between the temperatures T and the DAC codes is. Embodiments of the disclosure are advantageous, especially in high volume manufacturing environment because graph **300**, once established, provides the linear relationship between the DAC codes C and temperatures T on line **310**. As a result, corresponding temperatures T and DAC codes C can be easily identified. For example, given a DAC code C on the horizontal axis, a corresponding temperature T on the vertical axis can be identified using line **310**. Similarly, given a temperature T on the vertical axis, a corresponding DAC code on the horizontal axis can be identified using line **310**.

In an application, line **310** can be easily and economically established in a simple calibration process near room tem-

perature based on the linear relationship between temperatures T and DAC codes C. For example, a temperature sensor embodying a circuit **400** or **500** (e.g., the temperature sensing circuit) is subject to a first known temperature, e.g., temperature T_1 . Corresponding to temperature T_1 , a DAC code, e.g., code C_1 , is identified. The temperature sensing circuit is then subject to a second known temperature, e.g., temperature T_2 . Corresponding to temperature T_2 , a DAC code, e.g., code C_2 is identified. Based on the linear relationship between temperatures T and DAC codes C, temperatures T_1 and T_2 , and DAC codes C_1 and C_2 , line **310** can be readily established by various techniques known in the art, and embodiments of the disclosure are not limited to a particular technique. In a further application, for example, line **310**, once established, is analyzed to program a control circuit that can regulate temperatures T in a semiconductor chip using embodiments of the disclosure. For example, if a DAC code, e.g., code **C75**, would be identified at a particular operational moment of the chip, then this code **C75** corresponds to a temperature, e.g., temperature **T75** at 75°C . Because this temperature **T75** at 75°C indicates, for example, that the chip is running at **400** MHz and thus generates too much heat, the control circuit is programmed for the chip to run at a slower rate, e.g., **300** MHz to reduce the generated heat. Similarly, if a DAC code, e.g., code **C100**, is identified, then this code corresponds to a temperature, e.g., temperature **T100** at 100°C . Because this temperature **T100** at 100°C can, for example, damage the chip, the control circuit is programmed to shut down the chip when it recognizes code **C100**. The above examples are used to illustrate applications of the disclosure, and the disclosure is not limited to any particular example.

Circuit Providing V_{CTAT} and V_{CMP} —1st Embodiment

FIG. **4** shows a circuit **400** providing V_{CTAT} and V_{CMP} , in accordance with a first embodiment. For illustration purposes, FIG. **4** also includes comparator **100**. V_{CMP} , going through circuit **400** having a negative temperature coefficient circuit component canceling the temperature effect with a positive temperature coefficient circuit component results in a low or insignificant temperature coefficient.

Transistors M_1 , M_2 and amplifier A_1 constitute a current mirror wherein amplifier A_1 equalizes current I_{M1} and I_{M2} and voltages at NODE_1 and NODE_2 . Because I_{M1} equals to I_{M2} , I_M for illustration purposes, is used to refer to either I_{M1} or I_{M2} . At node NODE_1 $I_{M1}=I_{21}+I_{Q1}$ while at node NODE_2 $I_{M2}=I_{Q2}+I_{22}$. Bipolar transistor Q_1 is configured as a diode because a diode has negative temperature coefficient. V_{CTAT} is in fact V_{BE} (voltage from the base to emitter) of transistor Q_1 , and, for illustration purpose, is referred to as V_{BEQ1} . Bipolar transistor Q_2 is also configured as a diode, and for illustration purposes, the voltage across the base and emitter of transistor Q_2 is referred to as V_{BEQ2} . In the embodiment of FIG. **4**, CMOS technology is used and transistors Q_1 and Q_2 are implemented as diodes. Embodiments of the disclosure, however, can use diodes, instead of transistors, or any other devices that their operation depends on temperature. Two resistors R_{21} and R_{22} provide current paths for two currents I_{21} and I_{22} as shown. Because, in the embodiment of FIG. **4**, $R_{21}=R_{22}$, either resistor R_{21} or R_{22} may be referred to as R_2 . Similarly, because $I_{21}=I_{22}$ either current I_{21} or I_{22} may be referred to as I_2 . Resistor R_{21} is in parallel with transistor Q_1 while resistor R_{22} is in parallel with the series of resistor R_1 and transistor Q_2 . V_{CTAT} is the voltage at NODE_1 and also the voltage across V_{BE} of transistor Q_1 (e.g., V_{BEQ1}) such that it has a negative temperature coefficient. The voltage across resistor R_1 is the voltage difference between V_{BEQ1} and

V_{BEQ2} . As a result, it has a positive temperature coefficient. DAC resistors R_3 or DAC current I_{M4} provide voltage V_{CMP} wherein $V_{CMP}=I_{M4}*R_3$ at a particular value for I_{M4} or R_3 . In accordance with some embodiments, V_{CMP} is an insignificant temperature dependent voltage. To obtain different values of V_{CMP} , different values for DAC current I_{M4} and/or R_3 are obtained by varying the DAC codes corresponding to each current I_{M4} or varying resistor R_3 .

DAC transistors M_4 indicate that each current I_{M4} provided by a configuration of DAC transistors M_4 corresponds to a DAC code. Further, DAC transistors M_4 provide a mirrored current I_{M4} that multiplies current I_M . That is, $I_{M4}=N*I_M$ where N is the multiplication factor. In the embodiment of FIG. **4**, a DAC circuitry controls DAC transistors M_4 . That is, a digital value of the DAC circuitry corresponds to a value of current I_{M4} . For illustration purposes, if the DAC circuitry includes M number of input bits, and N numbers of outputs, then $N=2^M$. For example, if $M=2$ then $N=2^2$ or 4. If $M=3$ then $N=2^3$ or 8. If $M=4$, then $N=2^4$ or 16, etc. Some embodiments vary the DAC codes to obtain different values of I_{M4} and, effectively, different V_{CMP} . In an embodiment, changing the number of active transistors in DAC transistors M_4 changes the DAC codes and thus changes the value of N. Changing the value of N in turn changes the values of current I_{M4} . For example, a 2-bit DAC ($M=2$) results in $N=4$ (2^2) and thus 4 I_{M4} values, a 3-bit DAC ($M=3$) results in $N=8$ (2^3) and thus 8 I_{M4} values, and a 4-bit DAC ($M=4$) results in $N=16$ (2^4) and thus 16 I_{M4} values, etc. Further, because voltage V_{CMP} depends on current I_{M4} ($V_{CMP}=I_{M4}*R_3$), if current I_{M4} is provided by a DAC with 4 values, e.g., $I_{M4}(0:3)$, then V_{CMP} corresponds to 4 values $V_{CMP}(0:3)$. If current I_{M4} is provided by a DAC with 8 values, e.g., $I_{M4}(0:7)$, then V_{CMP} corresponds to 8 values $V_{CMP}(0:7)$. If current I_{M4} is provided by a DAC with 16 values, e.g., $I_{M4}(0:15)$, then V_{CMP} corresponds to 16 values $V_{CMP}(0:15)$, etc.

DAC resistors R_3 indicate that the values of resistor R_3 can also be varied by DAC codes. Similar to the situation of DAC transistors M_4 , an M-bit input DAC provides N outputs where $N=2^M$. Further, if this DAC controls DAC resistors R_3 , then N numbers of DAC codes (e.g., N numbers of DAC outputs) correspond to N values of resistor R_3 . Additionally, because $V_{CMP}=I_{M4}*R_3$, each value of resistor R_3 corresponding to a DAC code also corresponds to a value of V_{CMP} , similar to the DAC transistors M_4 explained above. Some embodiments vary the DAC codes to vary the value of R_3 , and, effectively, V_{CMP} . Those skilled in the art will recognize that there are many known techniques to provide various values of V_{CMP} using variations of resistors R_3 through DAC codes, and embodiments of the disclosure are not limited to a particular technique.

At node NODE_3 , because the input impedance of comparator **100** is significantly high, the current on line **120** is insignificant and can be disregarded. As a result:

$$V_{CMP}=I_{M4}*R_3$$

$$\text{Because } I_{M4}=N*I_M,$$

$$V_{CMP}=(N*I_M)*R_3$$

$$\text{Because } I_M=I_{M1}=I_{M2} \text{ and } I_{M2}=I_{Q2}+I_2,$$

$$V_{CMP}=N*(I_{Q2}+I_2)*R_3$$

$$\text{Because } I_{Q2}=(V_{BEQ1}-V_{BEQ2})/R_1=(V_T \ln(M_{21}))/R_1 \text{ and } I_2=V_{BEQ1}/R_2,$$

$$V_{CMP}=N*((V_T \ln(M_{21}))/R_1+V_{BEQ1}/R_2)*R_3 \quad (1)$$

In the above equation (1) V_T is a thermal voltage and $V_T=kT/q$ where k is the Boltzman constant and q is the unit charge. Further, M_{21} is the area ratio between diodes (or transistors) Q_2 and Q_1 . Based on equation (1), the temperature coefficient of R_1 and R_2 is canceled by the temperature coefficient of R_3 because R_1 and R_2 are in the denominator while R_3 is in the numerator. As a result, the temperature coefficient of V_{CMP} depends on that of the terms $(V_T \ln(M_{21}))$ and V_{BEQ1} , where $\ln(M_{21})$ is the natural log of M_{21} . Those skilled in the art will recognize that the temperature coefficient of V_{BEQ1} is negative while the temperature coefficient of $(V_T \ln(M_{21}))$ is positive, and they substantially cancel one another, resulting in V_{CMP} having a low or insignificant temperature coefficient. As V_{CMP} has a low or insignificant temperature coefficient, lines L_{VCMP} in FIG. 2 are substantially straight and substantially parallel to one another.

Circuit Providing V_{CTAT} and V_{CMP} —2nd Embodiment

FIG. 5 shows a circuit 500 providing V_{CTAT} and V_{CMP} , in accordance with a second embodiment. For illustration purposes, FIG. 5 also includes comparator 100. Similar to circuit 400, circuit 500 includes a negative temperature coefficient circuit component canceling the temperature effect with a positive temperature coefficient circuit component. In addition, circuit 500 also includes additional temperature curvature compensation circuits, and, as a result, V_{CMP} , going through circuit 500, results in an even more insignificant temperature coefficient.

Circuit 500 is similar to circuit 400 with the addition of resistors R_4 , R_5 , and transistors M_3 and Q_3 as shown. In the embodiment of FIG. 5 $R_4=R_5$ and either resistor R_4 or R_5 therefore may be referred to as resistor R_{45} . Transistor Q_3 is also configured as a diode similar to transistors Q_1 and Q_2 . Transistor M_3 acts as a current mirror wherein current I_{M3} has the same value as current I_M (i.e., I_{M1} or I_{M2}). In an embodiment, the area of transistor Q_3 is the same as that of transistor Q_1 .

Similar to circuit 400, because the input impedance to comparator 100 is significantly high, the current on line 120 is negligible. Therefore, at node NODE₃

$$V_{CMP}=I_{M4}*R_3$$

$$\text{Because } I_{M4}=N*I_M$$

$$V_{CMP}=(N*I_M)*R_3$$

$$\text{Because } I_M=I_{M1}=I_{M2} \text{ and } I_{M2}=I_{Q2}+I_2+I_{COMP},$$

$$V_{CMP}=N(I_{Q2}+I_2+I_{COMP})*R_3$$

$$\text{Because } I_{Q2}=(V_T \ln(M_{21}))/R_1, I_2=V_{BEQ1}/R_2 \text{ and } I_{COMP}=(V_{BEQ1}-V_{BEQ3})/R_4 \text{ or } (V_{BEQ3}-V_{BEQ1})/R_{45},$$

$$V_{CMP}=N[(V_T \ln(M_{21}))/R_1+V_{BEQ1}/R_2+(V_{BEQ1}-V_{BEQ3})/R_{45}]*R_3 \quad (2)$$

As discussed above, the term $(V_T \ln(M_{21}))$ has positive temperature coefficient, V_{BEQ1} has negative temperature coefficient. Further, $V_{BEQ3}-V_{BEQ1}$ also has positive temperature coefficient. The temperature coefficient of the terms $(V_T \ln(M_{21}))$, V_{BEQ1} and $V_{BEQ3}-V_{BEQ1}$ cancels one another, resulting in V_{CMP} with very low or insignificant temperature coefficient.

Those skilled in the art will recognize that, V_{CMP} in equation (2) has a temperature coefficient less than that of V_{CMP} in equation (1). As a result, lines L_{VCMP} in FIG. 2 resulted from

circuit 500 are straighter and thus more parallel than lines L_{VCMP} in FIG. 2 resulted from circuit 400. Consequently, line 310 resulted from circuit 500 is straighter than line 310 resulted from circuit 400. In brief, circuit 500 provides a more linear relationship between temperatures T and DAC codes C than circuit 400 does.

Voltage Dependent on Temperature as Proportional to Absolute Temperature (V_{PTAT})

FIG. 6 shows a comparator 600 in accordance with an embodiment related to a PTAT-type implementation. Reference voltage V_{PTAT} on line 610 is generated by a circuit (e.g., temperature sensing circuit) that will be described below. Similar to comparator 100, comparator 600 compares voltages V_{CMP} and V_{PTAT} , and provides resulting signal C_{POUT} on line 630. V_{CMP} in the embodiment of FIG. 6 is similar to that of in the embodiments related to the CTAT-type implementation explained above. V_{PTAT} is a proportional to absolute temperature (PTAT) reference voltage and is generated by the temperature sensing circuit at a particular temperature. For example, similar to the CTAT-type embodiments and in an application, the temperature sensing circuit is embedded as part of a sensor in a semiconductor device, e.g., a CPU. At operation, the CPU experiences a particular temperature (e.g., operational temperature) that is also experienced by the temperature sensing circuit, and V_{PTAT} is generated having this temperature as an input. In some embodiments, if V_{CMP} is slightly higher than (e.g., substantially equal to) V_{PTAT} then signal C_{POUT} is true, e.g., having a high logic. If V_{CMP} is lower than V_{PTAT} , then signal C_{POUT} is provided to another circuit (e.g., an adjusting circuit (not shown)) that changes the DAC codes which in turn change V_{CMP} until V_{CMP} is slightly higher than/substantially equal to V_{PTAT} . In effect, when V_{CMP} is equal to V_{PTAT} , the temperature experienced by the CPU and the temperature sensing circuit, e.g., temperature T_0 , is also the temperature at which the temperature sensing circuit provides V_{PTAT} . Further, this temperature T_0 corresponds to a DAC code, e.g., DAC code C_0 . In various embodiments, the temperatures at which the temperature sensing circuit provides V_{PTAT} and the DAC codes are substantially linearly related. As explained above, those skilled in the art will recognize that when the temperatures and the DAC codes are linearly related, the graph representing their relationship on a two dimensional axis is a straight line.

V_{PTAT} , V_{CMP} and Corresponding Temperatures

FIG. 7 shows a chart 700 illustrating the relationship between V_{PTAT} , V_{CMP} , and temperatures T , in accordance with an embodiment. As explained in the embodiments related to the CTAT-type implementation, each line L_{VCMP} shows the relationship between a voltage V_{CMP} and temperature T at a particular DAC code serving as an input for V_{CMP} to be generated. Varying the DAC codes from the least significant bit (LSB) to the most significant bit (MSB) provides lines L_{VCMP} . In various embodiments, due to the nature of a very small or insignificant temperature coefficient for V_{CMP} , lines L_{VCMP} are very close to parallel (e.g., substantially parallel) to one another in addition to being substantially straight. Based on the parallelism of lines L_{VCMP} and their being straight lines, embodiments provide linearity between the temperatures T and the DAC codes.

Line L_{VPTAT} shows the relationship between V_{PTAT} and temperature T . Those skilled in the art will recognize that line L_{VPTAT} has a positive slope and indicates that V_{PTAT} has a positive temperature coefficient. The intersection between

line $L_{V_{PTAT}}$ and a line $L_{V_{CMP}}$ indicates that V_{PTAT} equals to V_{CMP} at a particular temperature T that corresponds to a particular DAC code C . For example, point V_{PTAT0} indicates V_{PTAT} equals to V_{CMP} at a temperature T_0 that corresponds to a DAC code C_0 . Similarly, point V_{PTAT1} indicates V_{PTAT} equals to V_{CMP} at a temperature T_1 that corresponds to DAC code C_1 , and V_{PTATN} indicates V_{PTAT} equals to V_{CMP} at a temperature T_N that corresponds to a DAC code C_N , etc. In various embodiments, each point V_{PTATT} corresponds to the result in comparator **600** where V_{CMP} and V_{PTAT} are equal, e.g., when signal C_{POUT} is true, at a particular temperature T experienced by the temperature sensing circuit.

Temperatures and DAC Codes—PTAT-type

FIG. **8** shows a graph **800** with a line **810** indicating the relationship between temperatures T and DAC codes C related to PTAT. For example, T_0 corresponds to code C_0 , T_1 corresponds to code C_1 , T_N corresponds to code C_N , etc.

Embodiments of the disclosure provide the linearity between temperatures T and DAC codes C as much as possible, which is advantageous over prior art approaches that do not provide such linearity. This linearity results from the fact that lines $L_{V_{CMP}}$ in FIG. **7** are substantially straight and substantially parallel to one another. As explained above, in a 100% linearity situation, lines $L_{V_{CMP}}$ are 100% straight and thus 100% parallel to one another, which results in a line **810** being 100% straight. In other approaches lines $L_{V_{CMP}}$ are curved and/or not parallel to one another, which also causes line **810** to be curved. Those skilled in the art will recognize that the less curved the line **810** is, the more linear the relationship between the temperatures T and the DAC codes is. Embodiments of the disclosure are advantageous, especially in high volume manufacturing environment because graph **800**, once established, provides the linear relationship between the DAC codes C and temperatures T on line **810**. As a result, corresponding temperatures T and DAC codes C can be easily identified. For example, given a DAC code C on the horizontal axis, a corresponding temperature T on the vertical axis can be identified using line **810**. Similarly, given a temperature T on the vertical axis, a corresponding DAC code on the horizontal axis can be identified using line **810**.

In an application, line **810** can also be easily and economically established in a simple calibration process near room temperature based on the linear relationship between temperatures T and DAC codes C . For example, a temperature sensor embodying a circuit **400** or **500** (e.g., the temperature sensing circuit) with V_{CTAT} being replaced by V_{PTAT} generated by circuit **900** is subject to a first known temperature, e.g., temperature T_1 . Corresponding to temperature T_1 , a DAC code, e.g., code C_1 , is identified. The temperature sensing circuit is then subject to a second known temperature, e.g., temperature T_2 . Corresponding to temperature T_2 , a DAC code, e.g., code C_2 is identified. Based on the linear relationship between temperatures T and DAC codes C , temperatures T_1 and T_2 , and DAC codes C_1 and C_2 , line **810** can be readily established by various techniques known in the art, and embodiments of the disclosure are not limited to a particular technique. In a further application, for example, line **810**, once established, is analyzed to program a control circuit that can regulate temperatures T in a semiconductor chip using embodiments. For example, if a DAC code, e.g., code **C75**, would be identified at a particular operational moment of the chip, then this code **C75** corresponds to a temperature, e.g., temperature **T75** at 75°C .

Because this temperature **T75** at 75°C indicates, for example, that the chip is running at 400 MHz and thus gen-

erates too much heat, the control circuit is programmed for the chip to run at a slower rate, e.g., 300 MHz to reduce the generated heat. Similarly, if a DAC code, e.g., code **C125**, is identified, then this code corresponds to a temperature, e.g., temperature **T125** at 125°C . Because this temperature **T125** at 125°C can, for example, damage the chip, the control circuit is programmed to shut down the chip when it recognizes code **C125**. The above examples are used to illustrate applications of the embodiments, and the disclosure is not limited to any particular example.

Circuit Providing V_{PTAT} and V_{CMP}

In various embodiments, V_{CMP} related to PTAT-type embodiments is generated similarly to that of V_{CMP} related to CTAT-type, including using circuits **400** and **500** above.

FIG. **9** shows a circuit **900** used to generate V_{PTAT} , in accordance with an embodiment. For illustration purposes, FIG. **9** also includes comparator **600**. Circuit **900** is similar to circuit **400** except that circuit **900** does not include resistors corresponding to resistors R_{21} and R_{22} . Further, transistors M_6 and M_7 correspond to transistors M_1 and M_2 respectively; amplifier A_2 corresponds to amplifier A_1 ; resistor R_7 corresponds to resistor R_1 ; transistors Q_4 and Q_5 correspond to transistor Q_1 and Q_2 , respectively. Transistor M_5 corresponds to DAC transistors M_4 and resistor R_6 corresponds to DAC resistors R_3 . As a result, transistors M_6 , M_7 , and amplifier A_2 constitute a current mirror wherein amplifier A_2 equalizes current I_{M6} and I_{M7} and voltages at NODE_6 and NODE_7 . For illustration purposes, either I_{M6} or I_{M7} may be referred to as I_{M67} . Transistor M_5 provides a current I_{M5} that mirrors current I_{M67} . As a result, at NODE_4 , because input impedance of comparator **600** is significantly high, the current on line **610** is negligible. As a result,

$$V_{PTAT} = I_{M5} * R_6$$

Because $I_{M5} = I_{M6} = I_{M7} = (V_T \ln(M_{54})) / R_7$ where M_{54} is the area ratio of transistors Q_5 and Q_4

$$V_{PTAT} = ((V_T \ln(M_{54})) / R_7) * R_6$$

Because $V_T = (k * T) / q$

$$V_{PTAT} = ((k * T) \ln(M_{54}) / (q * R_7)) * R_6 \text{ or} \quad (3) \\ = ((k * R_6) \ln(M_{54}) / (q * R_7)) * T$$

As seen from equation (3), V_{PTAT} depends on T (or temperature) as proportional to absolute temperature. Similar to the CTAT-type embodiments, circuit **900** in conjunction with circuit **400** and DAC codes as explained above provides a linear relationship between DAC codes and temperatures in relation to V_{PTAT} . Further, circuit **900** in conjunction with circuit **500** provides a more linear relationship compared to that of circuit **900** in conjunction with circuit **400**.

DAC Transistors and DAC Codes

FIG. **10** shows a circuit **1000** illustrating an implementation example of DAC transistors M_4 that provides current I_{M4} (and thus V_{CMP}). Circuit **1000** includes four transistors M_{40} , M_{41} , M_{42} , and M_{43} , which are controlled (e.g., being turned on or off) by signals CT_0 , CT_1 , CT_2 , and CT_3 , respectively. For example, to turn each transistor M_{40} , M_{41} , M_{42} , or M_{43} on, each signal CT_0 , CT_1 , CT_2 , or CT_3 is activated (e.g., pulled to a low or 0), respectively. Conversely, to turn each

transistor M_{40} , M_{41} , M_{42} , or M_{43} off, each signal CT_0 , CT_1 , CT_2 , or CT_3 is deactivated (e.g., pulled to a high or 1). Because, in the embodiment of FIG. 10, $I_{M4} = I_{M40} + I_{M41} + I_{M42} + I_{M43}$, a value of current I_{M4} depends on each current I_{M40} , I_{M41} , I_{M42} , and I_{M43} . Further, turning on each transistor M_{40} , M_{41} , M_{42} , or M_{43} , provides each current I_{M40} , I_{M41} , I_{M42} , or I_{M43} to current I_{M4} .

FIG. 11 shows a table 1100 illustrating correspondence between values L and the number of transistors M_4 being turned on or off. When $L=0$, only transistor M_{40} is on. When $L=1$, transistors M_{40} and M_{41} are on. When $L=2$, transistors M_{40} , M_{41} , and M_{42} are on, and when $L=3$, all transistors M_{40} , M_{41} , M_{42} , and M_{43} are on.

FIG. 12 shows a table 1200 illustrating the relationship between values L and signals CT . Because, when $L=0$, only transistor M_{40} is on, signal CT_0 is low (or 0) while signals CT_1 , CT_2 , CT_3 are high (or 1). Because when $L=1$, transistors M_{40} and M_{41} are on, while transistors M_{42} and M_{43} are off, signals CT_0 and CT_1 are low while signals CT_2 and CT_3 are high. Because when $L=2$, transistors M_{40} , M_{41} , and M_{42} are on, and transistor M_{43} is off, signals CT_0 , CT_1 , and CT_2 are low while signal CT_3 is high. Similarly, because when $L=3$, all transistors M_{40} , M_{41} , M_{42} , and M_{43} are on, all signals CT_0 , CT_1 , CT_2 , and CT_3 are low. Depending on implementations, the values of L or the digital values of signals CT may be considered the digital codes corresponding to DAC currents I_{M4} (or voltage V_{CMP}) as explained above. For example, for each value or DAC code L from 0 to 3, there is a corresponding DAC current I_{M4} . For another example, for each code 0000, 0001, 0011, or 0111 of signals CT_0 , CT_1 , CT_2 , and CT_3 of table 1200, there is a corresponding DAC current I_{M4} .

FIGS. 10-12 show four transistors I_{M4} , four values of L and four signals CT to correspond to four values of DAC current I_{M4} for illustration purposes only. The disclosure is not limited to four DAC codes, but is applicable to various numbers of DAC codes and various other ways to provide the DAC codes.

A number of embodiments have been described. It will nevertheless be understood that various variations and modifications may be made without departing from the spirit and scope of the invention. For example, even though resistors (resistors R_1 , R_2 , etc., and others) are shown in the described embodiments, they may be replaced by a resistive component, a resistive network, or equivalences thereof. Circuits 400 and 500 are used to generate V_{CMP} and V_{CTAT} together, but different circuits may be used to generate V_{CMP} or V_{CTAT} separately. Circuits to generate V_{CTAT} and V_{PTAT} in the embodiments described above are for illustration purposes only, other circuits that provide a voltage complementary to absolute temperature or proportional to absolute temperature as appropriate are within scope of embodiments of the invention. The illustrative embodiments use the term "equal to" or "not equal to," but as long as two elements are close enough to be considered equal (e.g., substantially equal) by a person skilled in the art, they are within scope of embodiments of the invention, etc.

In accordance with an embodiment, a circuit includes a comparator, a first circuit, and a second circuit. The comparator has a first input node and a second input node. The first circuit is configured to output a temperature-dependent voltage at the first input node of the comparator. The first circuit includes a current mirror configured to generate a first reference voltage. The second circuit is configured to output a second reference voltage at the second input node of the comparator responsive to a digital code and the first reference voltage.

In accordance with another embodiment, a circuit includes a comparator, a first circuit, and a second circuit. The comparator has a first input node and a second input node. The first circuit is configured to output a temperature-dependent voltage at the first input node of the comparator. The first circuit includes a current mirror, a first transistor, a second transistor, a first resistive device, and a second resistive device. The current mirror is configured to generate a first reference voltage. The first transistor has a source coupled to a power node, a gate configured to receive the first reference voltage, and a drain. The second transistor has a collector coupled to a reference node, a base coupled to the reference node, and an emitter coupled to the drain of the first transistor. The first resistive device is coupled between a first node of the current mirror and the drain of the first transistor. The second resistive device is coupled between a second node of the current mirror and the drain of the first transistor. The second circuit is configured to output a second reference voltage at the second input node of the comparator responsive to a digital code and the first reference voltage.

In accordance with another embodiment, a circuit includes a comparator, a first circuit, and a second circuit. The comparator has a first input node and a second input node. The first circuit is configured to output a temperature-dependent voltage at the first input node of the comparator. The first circuit includes a current mirror, a first transistor, and a first resistive device. The current mirror is configured to generate a first reference voltage. The first transistor has a source coupled to a power node, a gate configured to receive the first reference voltage, and a drain. The first resistive device is coupled between the drain of the first transistor and a reference node. The second circuit is configured to output a second reference voltage at the second input node of the comparator responsive to a digital code and the first reference voltage.

Each claim in this document constitutes a separate embodiment, and embodiments that combine different claims and/or the above described embodiments are within scope of the invention and will be apparent to those skilled in the art after reviewing this disclosure.

What is claimed is:

1. A circuit comprising:

a comparator having a first input node and a second input node;

a first circuit configured to output a temperature-dependent voltage at the first input node of the comparator, the first circuit comprising a current mirror configured to generate a first reference voltage; and

a second circuit configured to output a second reference voltage at the second input node of the comparator responsive to a digital code and the first reference voltage.

2. The circuit of claim 1, wherein the first circuit is configured to generate a complementary-to-absolute-temperature (CTAT) voltage at the first input node of the comparator.

3. The circuit of claim 1, wherein the current mirror of the first circuit comprises:

an amplifier having a first input node, a second input node, and an output node;

a first transistor having a source coupled to a power node, a drain coupled to the first input node of the amplifier, and a gate coupled to the output node of the amplifier; and

a second transistor having a source coupled to the power node, a drain coupled to the second input node of the amplifier, and a gate coupled to the output node of the amplifier.

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4. The circuit of claim 1, wherein the first circuit further comprises:

a first transistor having a collector coupled to a reference node, a base coupled to the reference node, and an emitter coupled to a first node of the current mirror;

a second transistor having a collector coupled to the reference node, a base coupled to the reference node, and an emitter, a size of the second transistor is greater than that of the first transistor by a predetermined ratio; and
a first resistive device coupled between the second node of the current mirror and the emitter of the second transistor.

5. The circuit of claim 4, wherein the first circuit further comprises:

a second resistive device coupled between the first node of the current mirror and the reference node; and
a third resistive device coupled between the second node of the current mirror and the reference node.

6. The circuit of claim 1, wherein the second circuit comprises:

one or more transistors connected in parallel and coupled between the second input node of the comparator and a power node, the one or more transistors having corresponding one or more gates configured to receive the first reference voltage from the current mirror; and
one or more resistive devices connected in parallel and coupled between the second input node of the comparator and a reference node.

7. The circuit of claim 6, wherein the one or more transistors are configured to be turned on responsive to the digital code.

8. The circuit of claim 6, wherein the one or more resistive devices are configured to be electrically decoupled from the second input node of the comparator responsive to the digital code.

9. A circuit comprising:

a comparator having a first input node and a second input node;

a first circuit configured to output a temperature-dependent voltage at the first input node of the comparator, the first circuit comprising:

a current mirror configured to generate a first reference voltage;

a first transistor having a source coupled to a power node, a gate configured to receive the first reference voltage, and a drain;

a second transistor having a collector coupled to a reference node, a base coupled to the reference node, and an emitter coupled to the drain of the first transistor;

a first resistive device coupled between a first node of the current mirror and the drain of the first transistor; and
a second resistive device coupled between a second node of the current mirror and the drain of the first transistor; and

a second circuit configured to output a second reference voltage at the second input node of the comparator responsive to a digital code and the first reference voltage.

10. The circuit of claim 9, wherein the first circuit is configured to generate a complementary-to-absolute-temperature (CTAT) voltage at the first input node of the comparator.

11. The circuit of claim 9, wherein the current mirror of the first circuit comprises:

an amplifier having a first input node, a second input node, and an output node;

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a third transistor having a source coupled to a power node, a drain coupled to the first input node of the amplifier, and a gate coupled to the output node of the amplifier; and

a fourth transistor having a source coupled to the power node, a drain coupled to the second input node of the amplifier, and a gate coupled to the output node of the amplifier.

12. The circuit of claim 9, wherein the first circuit further comprises:

a third transistor having a collector coupled to the reference node, a base coupled to the reference node, and an emitter coupled to the first node of the current mirror;

a fourth transistor having a collector coupled to the reference node, the base coupled to the reference node, and an emitter, a size of the fourth transistor is greater than that of the third transistor by a predetermined ratio; and

a third resistive device coupled between the second node of the current mirror and the emitter of the fourth transistor.

13. The circuit of claim 12, wherein the first circuit further comprises:

a fourth resistive device coupled between the first node of the current mirror and the reference node; and

a fifth resistive device coupled between the second node of the current mirror and the reference node.

14. The circuit of claim 9, wherein the second circuit comprises:

a set of parallel-connected transistors coupled between the second input node of the comparator and the power node, the set of parallel-connected transistors having corresponding one or more gates configured to receive the first reference voltage from the current mirror; and
a set of parallel-connected resistive devices coupled between the second input node of the comparator and the reference node.

15. The circuit of claim 14, wherein the set of parallel-connected transistors are configured to be turned on responsive to the digital code.

16. The circuit of claim 14, wherein the set of parallel-connected resistive devices are configured to be electrically decoupled from the second input node of the comparator responsive to the digital code.

17. A circuit comprising:

a comparator having a first input node and a second input node;

a first circuit configured to output a temperature-dependent voltage at the first input node of the comparator, the first circuit comprising:

a current mirror configured to generate a first reference voltage;

a first transistor having a source coupled to a power node, a gate configured to receive the first reference voltage, and a drain; and

a first resistive device coupled between the drain of the first transistor and

a reference node; and
a second circuit configured to output a second reference voltage at the second input node of the comparator responsive to a digital code and the first reference voltage.

18. The circuit of claim 17, wherein the first circuit is configured to generate a proportional-to-absolute-temperature (PTAT) voltage at the first input node of the comparator.

19. The circuit of claim 17, wherein the current mirror of the first circuit comprises:

an amplifier having a first input node, a second input node, and an output node;

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a second transistor having a source coupled to the power node, a drain coupled to the first input node of the amplifier, and a gate coupled to the output node of the amplifier; and

a third transistor having a source coupled to the power node, a drain coupled to the second input node of the amplifier, and a gate coupled to the output node of the amplifier.

20. The circuit of claim **17**, wherein the first circuit further comprises:

a second transistor having a collector coupled to the reference node, a base coupled to the reference node, and an emitter coupled to a first node of the current mirror;

a third transistor having a collector coupled to the reference node, a base coupled to the reference node, and an emitter, a size of the third transistor is greater than that of the second transistor by a predetermined ratio; and

a second resistive device coupled between the second node of the current mirror and the emitter of the third transistor.

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